# Managed automated driving: a new way for safe and economic automation

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**Abstract**

Automated driving as discussed today within the community uses a pure vehicle-based automation. More advanced connected and cooperated AD use a light support of infrastructure but “the brain” is always installed in the vehicle. Some first demonstrations show that a support of the infrastructure might be useful. However, a radical shift to infrastructure-based automation has not been proposed so far. Managed automated driving (MAD) follows exactly this radical approach for a new level of automation. It is characterized by two key features: a) 100% monitoring by infrastructure with road capturing units (RCUs) – “at each lamp post a sensor” and b) 100% control by infrastructure with edge computing/back-end – “vehicle as simple actuator only”. In this paper we introduce MAD and discuss technical, economical and legal aspects of the unique opportunity. As an application example for MAD we use the already highly innovative modular vehicle concept “U-Shift”.

**Keywords**

System Engineering and Architecture; Impact, Cost-benefit and Risk Assessment

## The MAD approach and motivation

Today's transport sector is characterized by challenges related to $CO_2$-emissions, lack of space, noise and air pollution, as well as traffic jams. To counteract these challenges, especially in urban areas, the German Aerospace Center (DLR), Institute of Vehicle Concepts has developed the innovative U-Shift vehicle concept [1] together with MAD as an approach for a fast track to overall market introduction.

*U-Shift: An on-the-road-modular vehicle*

In the view of DLR, these societal, environmental and urban traffic challenges will only be solved by rethinking vehicles and their applications and making them more universal so that they can be used much more effective. With modular vehicles, for simultaneous passenger and freight transport, a 24h/d highly utilized operation is feasible. In order to make profitable use of the advantages of modularization, DLR has designed a new type of u-shaped modular vehicle concept for the transport of people and goods, called U-Shift (Figure 1).

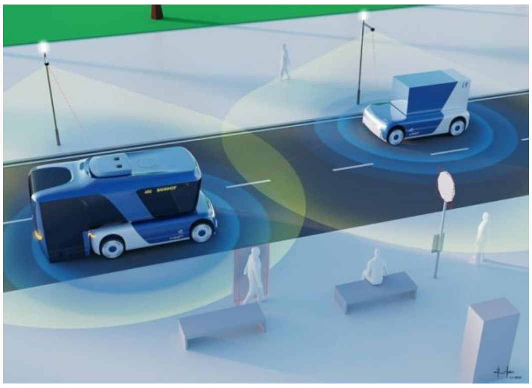

**Figure 1: U-Shift vehicle concept. The capsule on the left is for carry people, the one on the right is for cargo transport (source: own visualization by DLR employee Robert Hahn).**

The u-shaped driveboard for carrying various capsules has proven to be particularly flexible and efficient, as the integrated lifting chassis makes capsule replacement very easy. Depending on the application, 5 to 20 times more capsules are required than driveboards [2], which allows for a cost-effective and simple implementation. The vehicle technology of this unique vehicle design is very close to today's EVs extended with a new integrated lifting function integrated into the chassis of the driveboard. [1]

*Automation – Availability for market uptake*

**Key enabler for U-Shift is a ready to market specific automation solution**. Automated driving (AD) is in discussion since many years and the horizon for AD introduction varies a lot ranging from 2030 to 2060 for SAE level 5 (this is the result of a meta-analysis of 16 different works published between 2014 and 2019 [3]). A new CCAM partnership in Europe aims in general "to accelerate the implementation of innovative CCAM technologies and services" [4]. On this very high level, the industry identified several problem drivers from "Insufficient demand", "not yet sufficiently mature for market take-up" to "a lack a coherent, longer-term vision". Expected outcomes for 2030 should only be large scale demonstrations. Facing these problems with the AD market introduction, the automotive industry stays focused on vehicle-based automation and aims that AD technology is as part of the vehicle to have a big share on the future value chain. However, U-Shift team doesn't want to follow this slow evolutionary way and looked with a more holistic view, considering the entire transport system, to other domains. E.g. in the aeronautics the limited air space is controlled in different air traffic control (ATC) centers with a high efficiency and on a very high safety level. So, for AD in limited urban space a mandatory road traffic control is a simple lesson learned. The production industries follow successfully since decades the automation pyramid. In a top down approach all parameters in the whole plant are captured for highly effective fabrication. In safety critical industries redundancy is usual and each parameter is measured not only once. So, for AD a full capturing of the traffic scene in complex urban environment with a multilevel architecture is a second lesson learned from others. These very simple carry-over-principles should be used for vehicle automation in urban regions in form of "MAD".

*The MAD Hypothesis*

The need for infrastructure-based automation can be seen in a simple intellectual game. Assuming that automated vehicles will prevail in any traffic area, their number will increase; the implications for today's mainstream vehicle-based automation and infrastructure-based automation (MAD) on demand in computing power, energy or cost are in general different as the simple chart shows:

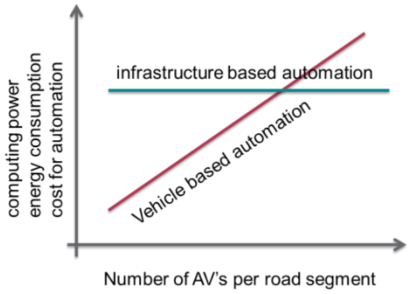


**Figure 2: MAD hypothesis (source: own visualization).**

In the case of vehicle-based automation, each of these automated vehicles will necessarily be fully equipped with automation components (sensors, computers etc.). It is an acknowledged fact that these components will generate corresponding costs per vehicle. In a macroeconomic consideration, the total costs will therefore increase linearly with the number of vehicles. The same applies to other systemic properties such as the installed computing power and thus also energy consumption in the vehicle. Especially this energy consumption for a vehicle-based automation is of high importance because it has to be provided by the traction battery. A simple analysis of today's mover systems shows that the batteries are designed to supply the automation and not for the actual driving function. However, reliable figures are not yet available. System suppliers assume that after optimization, an energy requirement of approx. 2.5 kW is still required for automation. Depending on the driving profile, over 40% of the battery capacity is required for automation. Especially in urban applications at low speeds or lower driving power demand this share is even higher. With infrastructure-based automation, costs and effort are almost independent of the number of automated vehicles in the planned application area. In this case, costs, energy consumption etc. are therefore constant in a first estimate. The initial investment in infrastructure is high but save operation is possible onwards from first operational vehicle.

For a certain number of automated vehicles, the two curves will definitely intersect. This leads to the hypothesis that an infrastructure-based automation as pursued with MAD will always have an advantage compared to today's common vehicle-based automation in the long run. This is a very important principle for all governments, municipalities, regions or nations considering the introduction of large number of automated vehicles e.g. by a public transport operator or logistic service provider. In the chapter economic analysis, we will show a first estimate for this break-even.

**MAD Architecture**

The MAD architecture allows distributing functions to control automated vehicles (AVs) into smart infrastructure. Possible functional components, that are needed to enable the U-Shift vehicle to cope with traffic situations autonomously, are perception tasks, path planning as well as maneuver planning tasks. Figure 3 gives an overview of the overall architecture. As a prerequisite, the infrastructure has to be aware of the position and states of all traffic participants and needs to communicate with the automated vehicles to distribute and especially to exchange information.

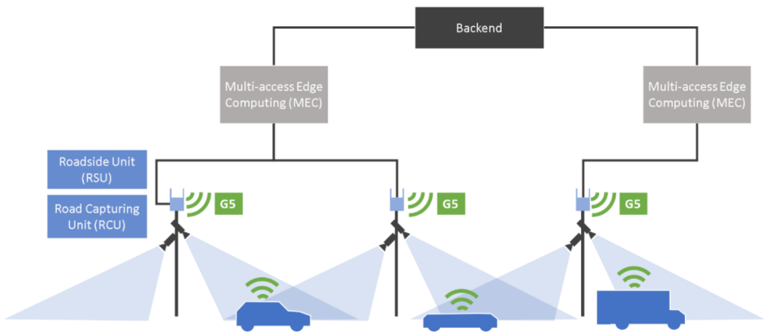


**Figure 3: Overview of the Managed Automated Driving architecture (source: own visualization).**

Local communication between the automated U-Shift vehicles and the infrastructure can be realized through wireless vehicular networks based on WLAN802.11p and ETSI ITS-G5 (see chapter *Local Communication*). So called road capturing units (RCUs) consist of multiple sensors, e.g. camera, lidar or radar. The RCUs are used to detect and track road users and obstacles on the road and reference them in a geo-coordinate frame, making it possible to transmit geo-referenced trajectories of traffic participants to U-Shift platforms in the field.

Roadside units and road capturing units are connected to a nearby MEC server [5] (multi-access edge computing). An MEC server is a decentralized computational unit that is spatially close to the RSUs and RCUs. Sensor data from the RCUs and the received messages from the RSUs are processed in the MEC server and a local environment model is created. With the help of this environment model, optimized maneuver planning and path planning can be accomplished inside the MEC-Server. The created trajectories will be sent from the RSU to the OBU in the AVs.

All MEC-Servers are connected to a global backend, allowing the backend to have information about all detected vehicles and fusing the different local environment models into a global environment model of the complete traffic system. This way, the information for smart fleet management, optimized booking services, global path optimization and monitoring are kept in the backend.

*Related Work*

There are various projects that investigate the use of infrastructure to support automated driving, as well as modular vehicle concepts. The project INFRAMIX prepares the road infrastructure with specific affordable adaptations and supports it with new models and tools, to accommodate for the step-wise introduction of automated vehicles. Additionally, a unified classification scheme for infrastructure support is defined (ISAD Levels). Projects like ICT4CART or MEC-View investigate different aspects of infrastructure-based automated driving. UNICARagil develops a driverless and modular vehicle that is able to use external sensors to extend the perception range. The projects can be accessed under [6]. Automated Valet Parking [7] is an automated parking service, where all required sensors are located inside the car park and the vehicles only need a V2X-communication unit to communicate with the infrastructure. The optimized transportation system based on autonomous driving electric vehicles (OTS) is focus of the OTS project of Siemens [8] where the impact on future transportation systems of infrastructure supported autonomous driving is investigated. Different logical layers and functional blocks are introduced that enable a holistic system view on the infrastructure-based automation, including monitoring and operational aspects.

*Shifting functionalities from automated vehicles into the infrastructure*

In conventional AVs, all functions, that are used to operate the vehicle, are realized inside the car. With the support of the infrastructure it is possible to shift dedicated functionalities from the AVs into the infrastructure. Table 1 shows an overview of the function distribution for the AD and the MAD case.

**Table 1: Allocation of the functionalities for the distinctions AD and MAD**

| Typ | Functions in the vehicle | Functions in the infrastructure |
|---|---|---|
| **AD** | • Drive by wire actuator<br>• Localisation system and high-precise maps<br>• Perception sensors<br>• Path planning unit<br>• Maneuver planning unit<br>• Communication unit (OBU)<br>• Trajectory regulation | • Fleet management<br>• Teleoperation system<br>• Communication unit (RSU) |
| **MAD** | • Drive by wire actuator<br>• Communication unit (OBU)<br>• Localisation system and high-precise maps (incl. odometry sensor)<br>• Trajectory regulation | • Localisation system and high-precise maps<br>• Perception sensors (RCU)<br>• Path planning unit<br>• Maneuver planning unit<br>• Fleet management<br>• Teleoperation system<br>• Communication unit (RSU) |

Typical implementations of autonomous driving (AD) place all functions inside the vehicle. Infrastructure might be supportive, but the focus lies on provided services like fleet management and route planning that have low latency and throughput demands. A clear advantage of this approach is, that there is no need for a stable low latency connection to infrastructure and that the vehicle is in general able to drive in areas without existing infrastructure. On the downside, there exist scenarios where the automated vehicles may quit their service by returning to a safe state due to a missing or faulty perception of the traffic scene.

In Managed Automated Driving (MAD), the vehicle contains a minimum setting of sensors and therefore most of the functionality is realized inside the infrastructure. The perception of the environment, path planning and maneuver planning are exclusively located in the infrastructure and for that reason a stable and fast connection between the vehicle and the infrastructure is necessary. An unstable connection or a loss of the connection leads to the AVs guidance into a safe state, such as an emergency break. If a stable connection is guaranteed, the perception of the MAD distinction has the potential of improved perception quality due to a mitigation of occlusion, a larger field of view and access to high performance computation hardware in the infrastructure that is not necessarily limited by power consumption and heating problems like on-board units.

*Local Communication*

Local communication between infrastructure (RSUs) and U-Shift vehicles is a key prerequisite of MAD and can be achieved by wireless vehicular networks (V2X), such as based on WLAN802.11p and ETSI ITS-G5 units that are already on the market and have been developed over multiple research projects during the last years [9]. Therefore, the *European Telecommunications Standards Institute (*ETSI) has standardized specific protocols and message types for specific tasks that allow sharing information with low latency and therefore enabling shifting tasks towards the infrastructure. For example, Cooperate Awareness Messages (CAM) are used to send the internal state of the vehicle, like position, heading, speed, vehicle type and Signal Phase and Timing (SPaT) and Map (MAP) messages are used to send information about traffic lights and the road geometry. Future message and protocol definitions include Cooperative Perception Messages (CPM) and Maneuver Coordination Messages (MCM) that put cooperated driving and infrastructure supported driving into a general focus, but which are still under standardization.

*Architectural Challenges*

The concept of Managed Automated Driving offers a lot of potential but also is subject to open challenges. One of these technical challenges is information fusion related problems. This for instance includes the identification and the registration of objects detected by the infrastructure with locally available data. Since communication is broadcast based, it is not trivial to associate external data with the internal view of the vehicles, which becomes inherently difficult in a minimum sensor setting in the vehicle. Still a major challenge is the communication between the automated vehicles and the infrastructure. For the MAD setting, it is evident that high quality communication with the infrastructure is needed, on the one hand to ensure safety, but on the other hand to provide the requested services by keeping uptimes of the system high. For high automation degrees like the U-Shift concept, it uncertain if the current standardized messages and protocols are suitable when all intelligence of the system is shifted to the infrastructure.

## Economic analysis investigating the MAD hypothesis

An essential objective of the work is to investigate the MAD hypothesis in Figure 2. In the following, an exemplary use case is identified in which the MAD concept is compared with the AD approach using the U-Shift fleet. The methodology of the economic analysis is then introduced, followed by a discussion of the results and a sensitivity analysis. Figure 4 illustrates the process.

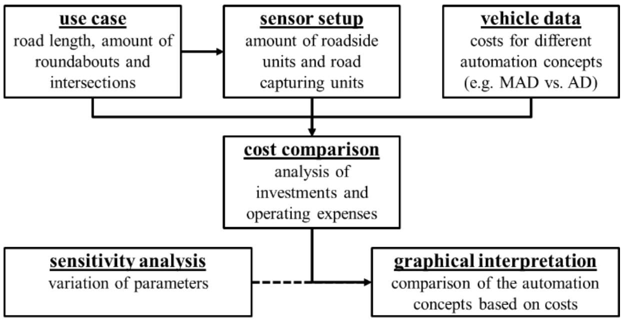


**Figure 4: Methodological process to evaluate the costs (source: own visualization).**

*Definition of a use case*

The district Stuttgart-Vaihingen is located in the southwest of Stuttgart at the upper edge of the "basin" and is the second largest district of Stuttgart with approx. 45,000 inhabitants. Due to its proximity to the Stuttgart motorway junction, it is well linked to the transport network. Besides the campus of the University of Stuttgart with various institutes, student residences but also external research facilities, Vaihingen also features Stuttgart's largest industrial area. In a first step, together with contact persons from the Stuttgart city administration, the Stuttgart Chamber of Commerce and Industry and the Institute for Road and Transportation Systems (University of Stuttgart), areas in Vaihingen were identified for which the use of U-Shift is potentially useful and where the characteristics of U-Shift -

"modular", "electrical", "autonomous" - can be used in a beneficial way. Figure 5 shows an aerial view of Vaihingen in which these regions are highlighted. This results in the route which has to be gradually extended with infrastructure sensors for the MAD automation (pink line).

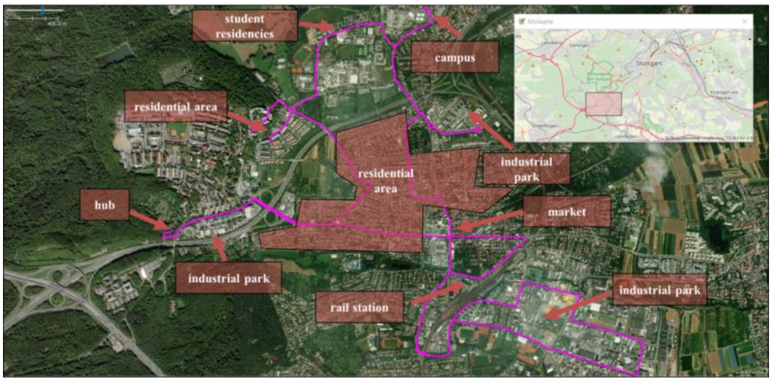


**Figure 5: Road network, which will be equipped with sensors for MAD in the use case (source: own visualization, generated with JOSM and using and aerial photograph of Esri).**

*Methodology for the economic analysis*

For the economic evaluation of the MAD concept a comparative cost calculation is performed, a static procedure of investment evaluation such as described by Schäfer (2005) [10]. This is composed of the main factors capital costs and operating costs; whereby here imputed depreciation and interest rates are not used as capital costs but rather the actual investment costs. This is sufficient to examine the MAD hypothesis. Income and business models will be analyzed in further work using the net present value method. For the MAD concept verification, the required infrastructure is first defined in the use case and then equipped with appropriate sensors. The proposed MAD sensor setup results in the number of sensor units required as a function of road length and the number of critical elements (roundabouts and intersections). Parallel to the costs of the sensor units, the costs for the driveboards are determined. These differ depending on the automation concept and are therefore significantly more expensive for the AD concept than for the MAD concept. On the other hand, the one-time initial investment for the infrastructure equipment is omitted in the AD concept. The formulas (1) and (2) describe the expenses for each automation concept in the initial year (investment in vehicles and infrastructure and operating costs for one year). The aim of the cost comparison is to determine from which number of vehicles moving on the equipped road sections the system costs for MAD are lower than for AD. The condition in formula (3) was derived for this purpose, resulting in formula (4). From the formulas it can be derived that the result for $N$ is the same whether $I_{V,rest}$ and $C_{V,rest}$ are considered or not. However, the graphical analysis is still conducted for both cases, so that the vehicle costs are also evident. A sensitivity analysis concludes the comparison.

$$E_{AD}(n) = n \cdot \left(I_{V,AD,auto} + I_{V,rest} + C_{V,AD,auto} + C_{V,rest}\right) \tag{1}$$

$$E_{MAD}(n) = n \cdot \left(I_{V,MAD,auto} + I_{V,rest} + C_{V,MAD,auto} + C_{V,rest}\right) + I_{Inf} + C_{Inf} \tag{2}$$

$$E_{AD} \geq E_{MAD}\ ! \tag{3}$$

$$N \geq \frac{I_{Inf} + C_{Inf}}{I_{V,AD,auto} - I_{V,MAD,auto} + C_{V,AD,auto} - C_{V,MAD,auto}} \tag{4}$$

*n: amount of vehicles; N: amount of vehicles from which AD costs more than MAD;*
*E: expenses (per year); I: investment costs; C: operating costs (per year);*
*V: vehicle related costs; Inf: infrastructure related costs;*
*auto: components related to automation;*
*rest: all vehicle components except the automation related ones;*
*in AD-operation no additional infrastructure related costs are assumed.*
*with:* $I_{V,AD,auto} > I_{V,MAD,auto}$ $C_{V,AD,auto} > C_{V,MAD,auto}$ *time frame: one year*

*Application of the methodology to the use case*

Based on the use case and the introduced MAD architecture, the two concepts, AD and MAD, are now compared from an economic perspective. All costs that are directly related to the vehicle or the infrastructure for autonomous driving are considered in the cost comparison. These consist of the investment costs for the driveboards and capsules as well as the MAD infrastructure (if applicable). In addition, the energy costs as the main drivers of the operating costs are considered, as these differ significantly in the individual automation approaches. The operating costs are calculated for one year. Other costs, such as labor costs, and revenues (e.g. income from passenger transport) are not part of the analysis at this point.

The comparison is based on the use case introduced above and a fleet with *n* driveboards and proportionately included capsules. The ratio “capsule to driveboard” is 4.44:1, based on an analysis of the transport tasks in this specific use case, which were developed in the project “U-Shift MAD” [11]. Since no business models are considered in this work, the individual transport tasks and the process for allocating the capsules to the driveboards will not be examined in depth at this point. Based on the analysis of the urban area and the transport demand, the route network was also defined in Figure 5. This comprises about 15 km of road including 100 intersections and 6 roundabouts.

The aim of the analysis is to find out from which number of driveboards the automation costs per driveboard are more favorable with the MAD architecture than with the AD approach. For this purpose, Figure 6 shows a comparison between AD and MAD based on the formulas (1) and (2). The calculation is based on Table 2.

**Table 2: Compilation of costs ($I_{V,Capsule,rest}$ is an average from different capsule types, because in the use case different application-optimized capsules are used).**

| | | unit | AD | MAD | | unit | AD | MAD |
|---|---|---|---|---|---|---|---|---|
| $I_{V,auto}$ | Driveboard | $EUR_{2020}$ | 11,000 | 1,500 | $C_{V,auto}$ | $EUR_{2020}$/a | 5,000 | 750 |
| | Capsule | $EUR_{2020}$ | 7,000 | - | $C_{V,rest}$ | $EUR_{2020}$/a | 8,700 | 8,700 |
| $I_{V,rest}$ | Driveboard | $EUR_{2020}$ | 62,000 | 62,000 | $I_{Inf}$ | $EUR_{2020}$ | - | 4,500,000 |
| | Capsule | $EUR_{2020}$ | 16,000 | 16,000 | $C_{Inf}$ | $EUR_{2020}$/a | - | 65,000 |
| Capsules without automation components | | | 30 % | - | | | | |
| Capsule to driveboard ratio | | | 4.44 | 4.44 | | | | |

At the intersection in Figure 6, *N* driveboards are implemented in the system (formula (4)). This means that from *N*=123 driveboards on, MAD is preferable for the road network / the use case in Figure 5.

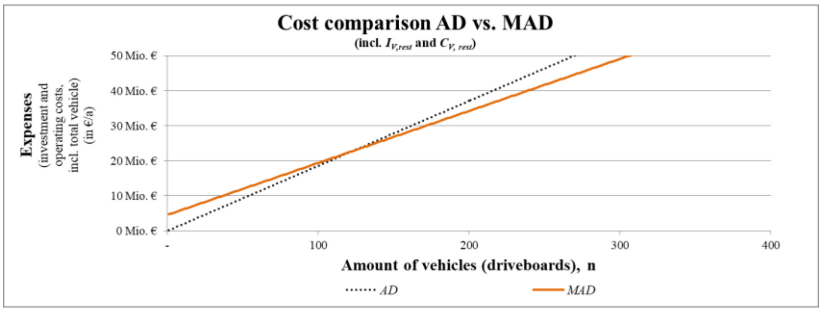


**Figure 6: Cost comparison of the AD- and MAD-concept, based on $E_{AD}$ and $E_{MAD}$ in the formulas (1) and (2) for the road network in Figure 5.**

The diagram in Figure 6 shows the total costs from automation-related and the remaining vehicle costs ($I_{V,rest}$ and $C_{V,rest}$). In a further analysis (Figure 7) only the automation-related costs are considered, which means that $I_{V,rest}$ and $C_{V,rest}$ are not considered. This way the initial hypothesis for MAD can be better mapped (refer to Figure 2). In this case $N$ equals 128 driveboards. Following the formulas (1) to (4), $N$ should be the same as in the first analysis, including $I_{V,rest}$ and $C_{V,rest}$. However, they differ by 5 driveboards. While it was possible to precisely break down the cost components in the driveboard and thus isolate the automation costs, this was not possible for the operating costs. Therefore, the energy consumption was derived proportionally for the automation components. This explains the small discrepancy between the two $N$.

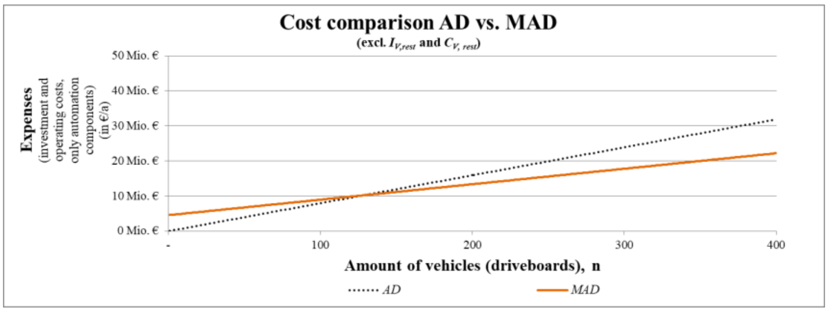


**Figure 7: Cost comparison of the AD- and MAD-concept for the road network in Figure 5, without considering $I_{V,rest}$ and $C_{V,rest}$ for better mapping of the MAD-hypothesis in Figure 2.**

Figure 8 illustrates how the MAD-graph in Figure 7 is composed: the costs for the infrastructure ($I_{Inf}$ and $C_{Inf}$) and the costs for the automation components in the driveboards and capsules ($I_{V,MAD,auto}$ and $C_{V,MAD,auto}$), which increase proportionally with n. On the basis of Figure 8 it becomes also evident why Figure 7 does not exactly resemble the hypothesis in Figure 2. While the MAD costs remain constant in the hypothesis, they grow in Figure 7. Figure 8 shows that the infrastructure share actually does not change even if the number of vehicles increases. However, MAD also requires rudimentary automation components in the vehicle, which is why the MAD curve also has a component that grows proportionally with the number of vehicles.

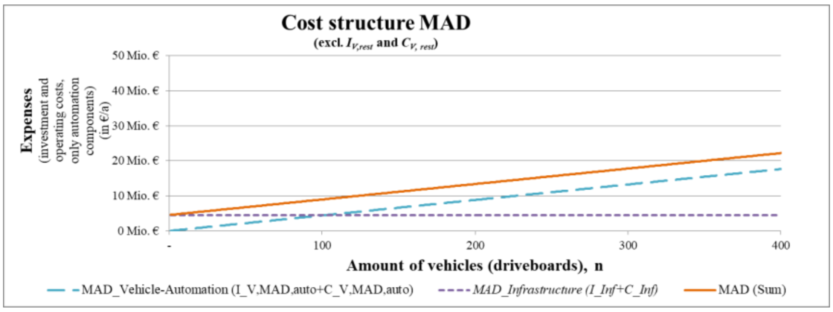


**Figure 8: Cost structure of the MAD for the road network in Figure 5, without $I_{V,rest}$ and $C_{V,rest}$.**

In the concluding sensitivity analysis (Table 3) different parameters are modified in order to examine their effect on the result. According to this, operating costs respectively energy consumption have scarcely any effect in this calculation. This is due, among other things, to the one-year period considered, which means that the investment costs are significantly higher. On the other hand, the critical factor N is reached much earlier if 1) the costs for infrastructure development decrease and / or 2) the automation costs of the vehicle fleet increase.

**Table 3: Sensitivity analysis (rounded to zero decimal places.)**

| Parameter | modification | *N* | *Difference to "Basis"* |
|---|---|---|---|
| No modification (Basis) | - | 128 | - |
| Energy consumption infrastructure | +20 % | 128 | ±0 |
| | -20 % | 127 | -1 |
| Energy consumption of the automation components in the driveboards and capsules | +20 % | 125 | -3 |
| | -20 % | 131 | +3 |
| Investment cost infrastructure | +20 % | 153 | +25 |
| | -20 % | 103 | -25 |
| Investment cost for driveboards and capsules | +20 % | 109 | -19 |
| | -20 % | 155 | +27 |

## Legal approval process

A legal approval process for automated and driverless driving is necessary for U-Shift MAD vehicles. Several laws from different jurisdictions (Figure 9) are presently in the way of fully automated driving in Germany and Europe. In order to analyze the necessary approval process, a literature research of the current situation as well as interviews about future perspectives with lawyers and experts from the technical control board (TÜV) were conducted. Since driverless automated driving is generally not permitted due to international regulations including the Vienna Convention on Road Traffic and UN regulation no. 79 regarding steering equipment, national individual approvals are currently used to register automated vehicles.

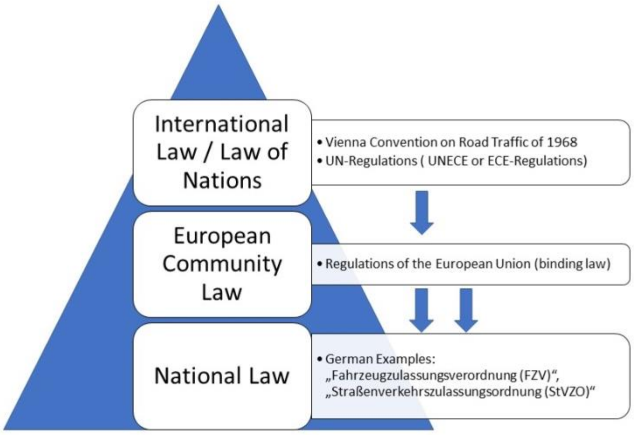


**Figure 9: National and international automation legislation (source: own visualization).**

In general, a new technology must first be safely implemented and available on the market before rules for approval and legislation are adapted to it. The more advanced the technology is and the further the respective manufacturers push the technology, the further the laws usually adapt. Among other things, questions of liability law must be clarified before a technology can become established on the road.

Currently there are efforts to change the **Vienna Convention on Road Traffic**, which is one of the international regulations that prevent fully driverless automated driving. This might be a chance to prepare the ground for automated driving. The Convention can be amended in a simplified procedure. It is not necessary for all contracting parties to negotiate an amendment of the agreement. Rather, a written procedure is possible in which a proposed amendment by only one contracting party leads to an effective amendment of the agreement if the other contracting parties do not oppose. [12]

**ECE (Economic Commission of Europe) regulations** are based on the 1958 Agreement on Vehicle Parts. The Administrative Committee out of this convention, composed of members of all contracting parties, shall adopt technical vehicle standards ("regulations"), inter alia, for the benefit of road safety (art. 1 para. 1). The contracting parties to the agreement are obliged to base their national type-approval procedure (art. 2) on all ECE regulations applicable to them. Amendments to regulations in the Administrative Committee require a 2/3 majority and are deemed to be adopted if they are not rejected by more than 1/3 of the Contracting States (art. 1 para. 2). They are therefore easier to obtain than the amendment of an international treaty. In Germany, ECE regulations can be brought into force by a regulation of the Federal Ministry of Transport. In addition, art. 8, para. 5 of the Vienna Convention, which refers to ECE regulations, opens up the possibility of various forms of automated driving – as long as there is still a driver. The provision continues to stand in the way of driverless driving. [12]

For the use case described above, the approval of U-Shift vehicles with a type approval for a small series is conceivable, since the expected vehicle volume is less than 1,000 units (the number of pieces is taken from German law). Here, the approval of the entire MAD system is to be considered, which consists of the vehicle (driveboard + capsule) and the infrastructure. For the approval of this new type of system, some basic principles have to be created which are a prerequisite for this use case. A first and in our view very important prerequisite is the creation of a standard for the infrastructure to which the approval process of the vehicles can refer to. Here, both the scope and the technical features of the infrastructure sensor system must be defined and standardized. Subsequently, it is necessary to create a process for the approval of these infrastructure elements in order to establish binding framework conditions such as quality, responsibilities, liability etc. One possibility is to classify roads or road sections in general according to their infrastructure equipment by ISAD levels. Automated vehicle approvals could then be linked to these levels. [13]

The current legal restrictions, in particular regarding the obligatory safety driver (SAE Level 4 and 5), are externally imposed factors. Their development regarding time and results is currently difficult to estimate. Unification of these standards at European level should be striven for in any case.

## Discussion and conclusions

We presented MAD, a strong infrastructure-based approach for vehicle automation in complex urban scenarios. The most suitable architecture for MAD combines key components such as RCU, MEC and TMC on several levels and a high-quality communication between vehicles and infrastructure is a key enabling factor. For a defined use case we have proven the MAD hypothesis, which states that infrastructure-based automation is preferable to the conventional vehicle-based approach for a large-scale market launch of automated driving. The legal situation for automated driving is becoming increasingly clearer. Registration restrictions for U-Shift and MAD are not expected. The proposed MAD approach und the built U-Shift vehicle will be further demonstrated and validated in different urban situations in the near future, such as at the German Mega Site in the European project SHOW (SHared automation Operating models for Worldwide adoption).

## Acknowledgments

We would like to thank all our colleagues who work with us on the MAD approach as well as the U-Shift vehicle for their valuable support, which helped to create this paper.

## Funding

The results on which this work is based were funded by the Federal Ministry for Economic Affairs and Energy of Germany (Bundesministerium für Wirtschaft und Energie) within the project “U-Shift MAD” [grant number: 01ME19005A]. The responsibility for the content of this work lies with the authors.

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